

Net Greenhouse Gas Emissions Affected by Sheep Grazing in Dryland Cropping Systems

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Sheep (*Ovis aries* L.) grazing is an inexpensive method of weed control in dryland cropping systems, but little is known about its effect on net greenhouse gas (GHG) emissions. We evaluated the effect of sheep grazing compared with herbicide application for weed control on GHG (CO_2 , N_2O , and CH_4) emissions from May to October 2010 and 2011, net global warming potential (GWP), and greenhouse gas intensity (GHGI) in a silt loam under dryland cropping systems in western Montana. Treatments were two fallow management practices (sheep grazing [GRAZ] and herbicide application [CHEM]) and three cropping sequences (continuous alfalfa [*Medicago sativa* L.] [CA], continuous spring wheat [*Triticum aestivum* L.] [CSW], and spring wheat–pea [*Pisum sativum* L.]/barley [*Hordeum vulgare* L.] hay–fallow [W-P/B-F]). Gas fluxes were measured at 3- to 14-d intervals with a vented, static chamber. Regardless of treatments, GHG fluxes peaked immediately following substantial precipitation (>12 mm) and N fertilization mostly from May to August. Total CO_2 flux from May to October was greater under GRAZ with CA, but total N_2O flux was greater under CHEM and GRAZ with CSW than other treatments. Total CH_4 flux was greater with CA than W-P/B-F. Net GWP and GHGI were greater under GRAZ with W-P/B-F than most other treatments. Greater CH_4 flux due to increased enteric fermentation as a result of longer duration of grazing during fallow, followed by reduced crop residue returned to the soil and/or C sequestration rate probably increased net GHG flux under GRAZ with W-P/B-F. Sheep grazing on a cropping sequence containing fallow may not reduce net GHG emissions compared with herbicide application for weed control on continuous crops.

Abbreviations: CA, continuous alfalfa; CHEM, herbicide application for weed control; CSW, continuous spring wheat; GHG, greenhouse gas; GHGI, greenhouse gas intensity; GRAZ, sheep grazing for weed control; GWP, global warming potential; MECH, tillage for weed control; SOC, soil organic carbon; W-P/B-F, spring wheat–pea/barley hay–fallow.

Sheep grazing during fallow periods or after crop harvest is often used to control weeds and pests, reduce feed costs, and increase nutrient cycling under dryland farming in the northern Great Plains (Johnson et al., 1997; Entz et al., 2002). Tillage and herbicide application to control weeds during fallow have been effective but are expensive, resulting in some of the highest variable costs for small grain production in Montana (Johnson et al., 1997). Other disadvantages of these practices are increased risks of soil erosion, organic matter mineralization, and contamination of soil, water, and air by herbicides that are hazardous to human and animal health (Fenster, 1997).

Agricultural practices contribute to three GHGs: CO_2 , N_2O , and CH_4 . About 6% of the total GHG emissions are contributed by agricultural practices in the United States (Greenhouse Gas Working Group, 2010; USEPA, 2011). Management practices have various effects on GHG emissions. Herbicide applica-

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tion to control weeds in no-till systems can lower CO₂ and N₂O emissions compared with tilled systems (Lemke et al., 1999; Mosier et al., 2006). Cropping systems can influence CO₂ and N₂O emissions by affecting the quality and quantity of crop residue returned to the soil (Mosier et al., 2006; Sainju et al., 2008). Nitrogen fertilization typically has a stimulatory effect on N₂O emissions (Mosier et al., 2006; Dusenbury et al., 2008) but a variable effect on CO₂ and CH₄ emissions (Bronson and Mosier, 1994; Al-Kaisi et al., 2008). Enteric fermentation from sheep during grazing can be the primary source of CH₄ emissions in grazed systems, and the return of feces and urine to the soil can generate GHGs (Judd et al., 1999).

Leguminous crops can be a source of N₂O emissions during residue decomposition because of their greater N concentration than nonleguminous crops. Lemke et al. (1999) and Mosier et al. (2006) found greater N₂O emissions with legumes than with nonlegumes due to the presence of rhizobium bacteria in root nodules. Because of a lower C/N ratio, legumes decompose more rapidly than nonlegumes, thereby increasing N₂O emissions (Huang et al., 2004).

Management practices can also indirectly affect GHG emissions by altering soil temperature and water content because these parameters are directly related to gas emissions (Parkin and Kaspar, 2003; Dusenbury et al., 2008; Liebig et al., 2010). Sheep grazing can increase soil temperature and reduce water content by consuming crop residues (Judd et al., 1999), while herbicide application (no-till) can conserve soil water and reduce temperature because of decreased soil disturbance and increased residue accumulation at the soil surface (Curtin et al., 2000). Similarly, the cropping system and crop type can influence soil temperature and water content by affecting shade intensity, evapotranspiration, and the amount of crop residue returned to the soil (Curtin et al., 2000). Higher water contents in no-till soils usually result in restricted aeration and greater denitrification rates and N₂O emissions than in conventionally tilled soils (Doran, 1980). In the northern Corn Belt, where soil water is more abundant than in other regions of the United States due to fairly uniform precipitation throughout the year, Johnson et al. (2010) found no significant effect of crop rotation on N₂O emissions.

Besides GHG emissions, factors such as soil C sequestration and CO₂ produced during farm operations and N fertilization can influence net GWP and GHGI. It is the balance between soil organic C (SOC) storage and N₂O and CH₄ emissions that typically control net GWP and GHGI (Robertson et al., 2000; Mosier et al., 2006). To understand agriculture's impact on radiative forcing, all sources and sinks of CO₂, N₂O, and CH₄ in the agroecosystem should be considered (Robertson et al., 2000). A system becomes a source of net GWP and GHGI if the values are positive and a sink if they are negative (Robertson et al., 2000; Mosier et al., 2006).

Little information is available about the effect of sheep grazing on GHG emissions, net GWP, and GHGI under dryland cropping systems in the northern Great Plains. We hypothesized that sheep grazing under a perennial crop (alfalfa) would reduce

GHG emissions, net GWP, and GHGI compared with herbicide applications for weed control under annual crops. Our objectives were to: (i) evaluate the effects of fallow management (sheep grazing and herbicide application for weed control), cropping sequence (CA, CSW, and W-P/B-F), and crop species (spring wheat, pea/barley hay, and fallow within W-P/B-F) on GHG emissions from May to October 2010 and 2011 in western Montana; and (ii) determine net GWP and GHGI based on soil respiration and SOC, and (iii) identify management practices that reduce net GHG emissions.

MATERIALS AND METHODS

Site and Treatment Descriptions

The experiment was conducted from 2009 to 2011 at the Fort Ellis Research and Extension Center, Montana State University (45°40' N, 111°2' W, altitude 1468 m), approximately 8 km east of Bozeman, MT. Total annual precipitation (120-yr average) at the site is 453 mm, and the mean monthly air temperature ranges from -6°C in January to 19°C in July. The soil is a Blackmore silt loam (a fine-silty, mixed, superactive, frigid Typic Argiustoll) derived from calcareous loess with 0 to 4% slope, with 250 g kg⁻¹ sand, 500 g kg⁻¹ silt, and 250 g kg⁻¹ clay and a pH of 6.7 at the 0- to 15-cm depth. Previous treatments (2004–2008) at the site included three fallow management practices for weed control (sheep grazing, tillage, and herbicide application) as the main plot and three cropping sequences (CSW, spring wheat–fallow, and winter wheat–fallow) as the split-plot variable. Soil total C content at the 0- to 30-cm depth in autumn 2008 was 82.4, 91.7, and 95.5 Mg C ha⁻¹ and total N was 7.43, 8.28, and 8.33 Mg N ha⁻¹ in the spring wheat–fallow, CSW, and winter wheat–fallow treatments, respectively, regardless of fallow management practice.

For this study, the same main-plot fallow management treatments from the previous experiment (CHEM, GRAZ, and tillage [MECH]) were continued. Similarly, in the split-plot treatment, CSW from the previous experiment was continued, but spring wheat–fallow and winter wheat–fallow were replaced by CA and the W-P/B-F rotation. The GRAZ treatment consisted of grazing with a group of western white-faced sheep at a stocking rate of 58 to 101 sheep d⁻¹ ha⁻¹. Sheep were grazed before planting in the early spring and after crop harvest in the fall in CSW. In addition to these periods, sheep were also grazed during summer fallow in the W-P/B-F rotation. In CA, grazing occurred in the fall. Grazing ended when about 47 kg ha⁻¹ or less of crop residue and weeds remained in the plot. Sheep were housed in the barn before being grazed in the plots. The CHEM treatment consisted of applications of a mixture of post-emergence herbicides (glyphosate [*N*-(phosphonomethyl)glycine at 0.42 kg a.i. ha⁻¹] and the dimethylamine salt of dicamba [3,6-dichloro-2-methoxybenzoic acid] at 0.28 kg a.i. ha⁻¹) before planting and after crop harvest for weed control in spring wheat and pea/barley hay in CSW and W-P/B-F. The MECH treatment consisted of tilling plots with a Flexicoil harrow (John Deere 100) to a depth of 15 cm during fallow to control weeds as needed and for seedbed preparation.

For alfalfa in CA, herbicides in the CHEM treatment and tillage in the MECH treatment were applied before planting in spring 2009, after which no further treatments occurred. While perennial alfalfa was grown in CA and annual spring wheat in CSW, W-P/B-F was a 3-yr rotation of spring wheat, a pea/barley hay mixture, and fallow (three crop phases), with each phase present in every year. The CHEM with CSW was the control treatment. Treatments were arranged in a randomized complete block with three replications. The size of the main plot was 91.4 by 76.0 m, and the split plot was 91.4 by 15.2 m.

Crop Management

Nitrogen fertilizer as urea (45% N) was broadcast to spring wheat and pea/barley hay at planting in May 2009 to 2011. While N fertilizer was left at the soil surface in the GRAZ and CHEM treatments, it was incorporated to a depth of 15 cm using tillage in the MECH treatment. Nitrogen fertilization rates to spring wheat were 202 kg N ha⁻¹ in CSW and 252 kg N ha⁻¹ in W-P/B-F. Similarly, the N rate applied to pea/barley hay was 134 kg N ha⁻¹. Nitrogen rates depended on yield goals, which were 3.9 Mg ha⁻¹ for spring wheat grain in CSW and 4.8 Mg ha⁻¹ in W-P/B-F and 8.9 Mg ha⁻¹ for pea/barley hay. Nitrogen rates were adjusted to the soil NO₃-N content to a depth of 60 cm measured after crop harvest in the fall of the previous year before N fertilizer was applied to spring wheat and pea/barley hay. No N fertilizer was applied to alfalfa or during summer fallow in W-P/B-F. Because the soil contained higher levels of extractable P (>70 mg P kg⁻¹) and K (>395 mg K kg⁻¹) at the 0- to 15-cm depth (Sainju et al., 2011), no P or K fertilizers were applied.

Immediately after tillage and fertilization in mid-May 2009 to 2011, McNeal spring wheat (Foundation Seed, Montana State University) was planted at 90 kg ha⁻¹ in CSW and W-P/B-F using a double disc opener with a row spacing of 15 cm. Using the same equipment, Haybet barley hay (Montana State University stock) was planted at 50 kg ha⁻¹ and Arvika pea hay (Circle S Seed) was planted at 112 kg ha⁻¹ in W-P/B-F with a row spacing of 15 cm. Similarly, Haygrazer alfalfa (Browning Brothers Seed) was planted at 22 kg ha⁻¹ with a JD 750 drill at a row spacing of 20 cm. In September, total crop biomass (containing grain, stems, and leaves in spring wheat and stems and leaves in pea/barley hay and alfalfa) was collected 2 d before crop harvest from two 0.5-m² areas. Biomass was oven dried at 70°C for 3 to 4 d for dry matter yield determination. Spring wheat grain yield (at 12–13% moisture content) was determined from a 1389-m² area in 2010 and 1240 m² in 2011 using a combine harvester. Spring wheat biomass (stems and leaves) was determined by deducting the grain yield from the total biomass. Spring wheat biomass after grain harvest and pea/barley and alfalfa forages were removed for hay with a self-propelled mower-conditioner and square baler in the CHEM and MECH treatments. In the GRAZ treatment, sheep were allowed to graze over the spring wheat, pea/barley hay, and alfalfa biomass residue.

Greenhouse Gas Sampling and Analysis

The GHG emissions were measured in only two fallow management practices (CHEM and GRAZ) with all cropping sequences in 2010 and 2011 due to resource constraints. Greenhouse gas sampling and analysis were followed using vented, static chambers as described by Hutchinson and Mosier (1981). The chamber was made from a nonreactive polyvinyl chloride pipe (1 cm thick) and Plexiglas material (1 cm thick) and consisted of two parts: an anchor (22.5 cm tall by 20 cm in diameter) and a lid (10 cm tall by 20 cm in diameter). The anchor was inserted into the soil to a depth of 15 cm, leaving 7.5 cm above the surface. One end of the lid was sealed with Plexiglas using permanent glue and tape and contained ports for ventilation and gas sampling. The outer edge of the other end of the lid was attached with a soft rubber sheet that was lowered to seal the anchor during gas sampling so that no exchange of gases occurred between the inside and the outside of the chamber. Anchors were removed during planting and fertilization and reinstalled near the original place in leveled areas covering crop rows and interrows in each treatment and year. A carpenter's level was used to level the anchor in the north–south and east–west directions. A 24-h equilibration period after anchor installation was allowed before gas sampling to avoid errors due to soil disturbance. Two chambers were installed per plot to reduce spatial variability in GHG measurement, and the average value was used for each treatment for data analysis. The total headspace volume of the chamber was determined by adding the inside volumes of the anchor above the soil surface and the lid.

Surface soil CO₂, N₂O, and CH₄ fluxes were measured from 0800 to 1200 h at 3- to 14-d intervals, depending on crop growth, from May to October 2010 and 2011. Gas samplings occurred during the same period each day to reduce the diurnal effect of temperature on GHG fluxes (Parkin and Kaspar, 2003). Measurements were made at 3-d intervals during the first approximately 2 mo after planting to measure CO₂ flux due to root and microbial respiration during active crop growth, N₂O flux due to N fertilization, and GHG fluxes due to major precipitation events. As the rate of crop growth and precipitation events declined and the effect of N fertilizer on the N₂O flux diminished due to N uptake by the crop, measurements were made at 7-d intervals thereafter until crop harvest. Because few GHG emissions occur after crop harvest in the fall due to reduced soil temperature and water content (Dusenbury et al., 2008; Liebig et al., 2010), measurements were made at 14-d intervals during this period.

At gas sampling, the lid was placed on top of the anchor and the rubber sheet from the lid was lowered to seal the anchor. Gas samples were collected from the port by inserting a needle attached to a 20-mL syringe and transferred to pre-evacuated 12-mL vials sealed with butyl rubber septa (Labco Ltd.). Samples were collected at 0, 20, and 40 min to calculate the flux. Concentrations of CO₂, N₂O, and CH₄ in the gas samples inside the vials were determined with a gas chromatograph (Varian Model 3800) in the laboratory. The gas chromatograph was fully automated with thermoconductivity, flame ionization, and electron capture

detectors for analysis of CO₂, CH₄, and N₂O concentrations, respectively, in one gas sample. Gas flux was calculated as changes in either linear or curvilinear concentration gradient with time (Hutchinson and Mosier, 1981; Liebig et al., 2010). Total fluxes during the measurement period from May to October each year were calculated by linearly interpolating data points and integrating the underlying area (Gilbert, 1987). At the time of gas sampling, at the 0- to 15-cm depth, soil temperature was measured with a temperature probe and water content was determined gravimetrically by collecting field-moist soil samples with a hand probe (2-cm i.d.) near the chamber and oven drying at 105°C. Volumetric soil water content was determined by multiplying the gravimetric water content by the bulk density of the soil core measured at the time of sampling. Because the soils were frozen (<0°C) to >1-m depth and insignificant fluxes generally occur from November to April, except N₂O flux in the early spring (Dusenbury et al., 2008; Liebig et al., 2010), GHG fluxes and soil temperature and water content were not measured during this period.

Net Global Warming Potential and Greenhouse Gas Intensity

For calculating net GWP and GHGI, CO₂, N₂O, and CH₄ fluxes were annualized by incorporating the estimated missing values during the winter (November–April) as shown by Liebig et al. (2010) in North Dakota (15% for CO₂, 12% for N₂O, and 30% for CH₄). The CO₂ equivalents of N₂O and CH₄ fluxes were calculated by multiplying their values by 298 and 25, respectively (Intergovernmental Panel on Climate Change, 2007). Soil respiration was calculated by multiplying CO₂ flux by 0.7 to eliminate root respiration (Mosier et al., 2006). Similarly, the CO₂ equivalent of fuel used for farm operations (tillage, planting, P and K fertilization, herbicide application, and harvest) was estimated as shown by West and Marland (2002) and that for N fertilizer manufacture and application as shown by Follett (2001).

For determining SOC, soil samples were collected to a depth of 15 cm from five places per plot after crop harvest in the fall of each year with a hand probe (5-cm i.d.), composited, and air dried. A subsample was ground to 0.5 mm for determination of SOC concentration using C and N analyzer (Leco Corp.). Because the soil bulk density at 0 to 15 cm was not different among treatments and years, an average bulk density of 1.42 Mg m⁻³ was used to convert SOC values from concentration (g kg⁻¹) to content (kg ha⁻¹). The CO₂ equivalent of the soil C sequestration rate for each treatment was calculated by the difference in SOC contents (kg CO₂-C ha⁻¹) at the 0- to 15-cm depth from 2009 to 2011 and divided by the number of years. Because the aboveground crop biomass (grain, stems, and leaves) was removed in all treatments, the CO₂ equivalent of the previous year's crop root and rhizodeposit C was used to determine the net GWP and GHGI based on soil respiration (Mosier et al., 2006). Root and rhizodeposit C for spring wheat (similar to durum), pea/barley hay, and alfalfa were estimated as shown by Sainju and Lenssen (2011).

The GWP based on soil respiration was calculated by deducting the CO₂ equivalent of the previous year's root and rhizode-

posit C from the sum of the CO₂ equivalents of farm operations, N fertilization, soil respiration, N₂O and CH₄ fluxes, and CH₄ flux from enteric fermentation during sheep grazing (Mosier et al., 2006). Similarly, the net GWP based on SOC was determined by deducting the CO₂ equivalent of the soil C sequestration rate from the sum of the CO₂ equivalents from farm operations, N fertilization, N₂O and CH₄ fluxes, and CH₄ flux from enteric fermentation during sheep grazing (Robertson et al., 2000; Liebig et al., 2010). The GHGI based on soil respiration and SOC was calculated by dividing the net GWP by the annualized aboveground grain and/or biomass yield (Mosier et al., 2006).

Statistical Analysis of Data

Data for soil temperature, water content, GHG fluxes, net GWP, and GHGI were statistically analyzed using the analysis of repeated measures procedure in the SAS MIXED model (Littell et al., 2006). Fallow management was considered as the main-plot treatment and a fixed effect. Cropping sequence was considered as the split-plot treatment and another fixed effect. Gas and soil sampling dates (or year) were considered as repeated-measure variables. Random effects were replication and replication × fallow management interaction. In the W-P/B-F rotation, data were averaged across cropping phases, and the average value was used for the rotation for analysis (crop biomass and grain yields during the fallow phase were considered zero during data averaging). To determine the effect of crop species, data for GHG fluxes, soil temperature, and water content within W-P/B-F were also analyzed by cropping phase. Means were separated by using the least square means test when treatments and interactions were significant (Littell et al., 2006). Statistical significance was evaluated at $P \leq 0.05$ unless otherwise stated.

RESULTS AND DISCUSSION

Precipitation and Air Temperature

Daily total precipitation varied during the crop growing season (May–October), with most of it occurring in May and June (Fig. 1). Monthly total precipitation in May and June, the active crop growing season, was greater in 2010 (198 mm) than the 113-yr average (143 mm). Similarly, total precipitation in August and September was greater in 2010 (83 mm) but lower in 2011 (40 mm) than the 113-yr average (73 mm). Growing season precipitation accounted for 74 to 77% of the total annual precipitation in 2010 and 2011. Both growing season and total annual precipitation were greater in 2010 (350 and 470 mm, respectively) than in 2011 (249 and 323 mm, respectively) and the normal (249 and 454 mm, respectively).

Daily average air temperature increased from May to August and then declined until October in 2010 and 2011 (Fig. 1). Monthly average air temperature from May to August was lower in 2010 (14.3°C) than in 2011 (15.5°C) and the 113-yr average (15.6°C). The average air temperature from September to October was, however, greater in 2010 (11.5°C) and 2011 (12.5°C) than the 113-yr average (10.0°C). The growing season average air temperature was greater in 2011 (14.4°C) than in 2010 (13.5°C)

and the 113-yr average (13.8°C), but the annual average temperature was similar in all years (6.2–6.9°C). Variations in precipitation and air temperature may influence soil temperature and water content, which indirectly influence GHG emissions, as described below.

Soil Temperature and Water Content

Soil temperature and water content at 0 to 15 cm varied with cropping sequence and date of measurement, with significant interactions for fallow management × cropping sequence and cropping sequence × date of measurement in 2010 and 2011 (Table 1). The effects of fallow management and its interaction with date of measurement on soil temperature and water content were not significant.

Soil temperature increased from May to August and then declined, regardless of treatment (Fig. 2). Soil temperature was

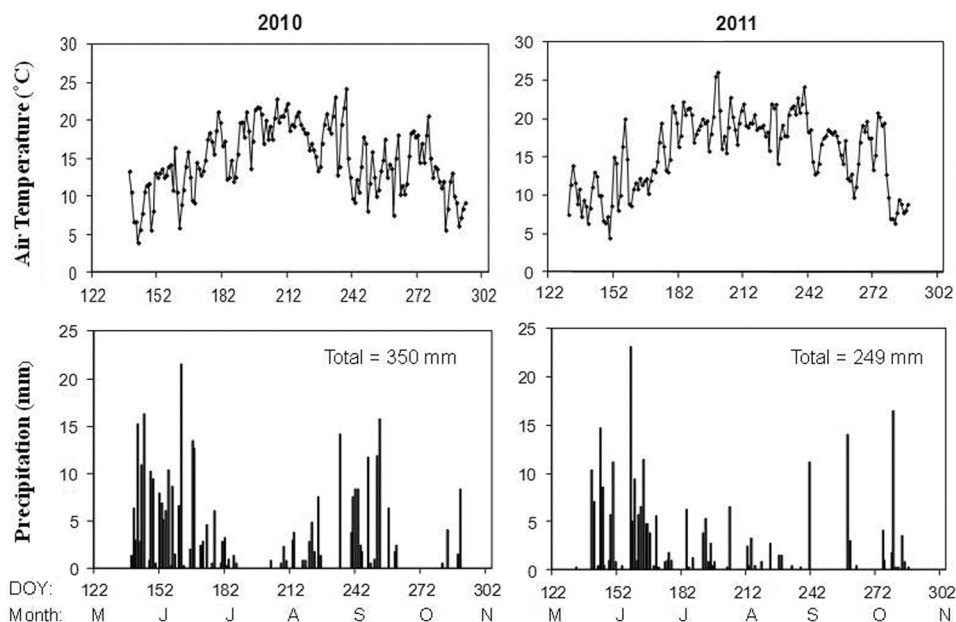


Fig. 1. Daily average air temperature and total precipitation from May to October 2010 and 2011 at the experimental site; DOY denotes day of the year and M to N denote months from May to November. Also shown is total precipitation during the study period from May to October.

greater for CSW and W-P/B-F than CA in July 2010 and June to August 2011. Averaged across measurement dates, soil temperature was greater for W-P/B-F than CA under CHEM and greater for CSW and W-P/B-F than CA under GRAZ in 2010

Table 1. Effects of fallow management and cropping sequence on soil temperature and water content at the 0- to 15-cm depth averaged across measurement dates from May to October 2010 and 2011.

Fallow management†	Cropping sequence‡	Soil water content			Soil temperature		
		2010	2011	Mean	2010	2011	Mean
		m ³ m ⁻³			°C		
CHEM	CA	0.230 b§	0.227 ab	0.229 a	14.52 b	13.92 b	14.22 a
	CSW	0.235 b	0.223 bc	0.229 a	15.05 ab	14.77 a	14.91 a
	W-P/B-F	0.242 a	0.224 b	0.233 a	15.39 a	14.87 a	15.13 a
GRAZ	CA	0.229 b	0.236 a	0.232 a	14.79 b	13.43 b	14.11 a
	CSW	0.230 b	0.210 c	0.220 a	15.95 a	14.83 a	15.14 a
	W-P/B-F	0.232 b	0.215 c	0.224 a	15.41 a	14.79 a	15.10 a
<u>Means</u>							
CHEM		0.236 a	0.220 a	0.230 a	14.99 a	14.52 a	14.75 a
GRAZ		0.230 a	0.225 a	0.225 a	15.22 a	14.35 a	14.78 a
	CA	0.230 b	0.232 a	0.231 a	14.65 b	13.67 b	14.16 b
	CSW	0.232 b	0.217 b	0.225 a	15.25 a	14.80 a	15.03 a
	W-P/B-F	0.237 a	0.219 b	0.228 a	15.40 a	14.83 a	15.12 a
<u>Significance</u>							
Fallow management (FM)		NS	NS	NS	NS	NS	NS
Cropping sequence (CS)		***	***	NS	***	***	***
FM × CS		*	**	NS	*	***	NS
Date of measurement (D)		***	***	NS	***	***	NS
FM × D		NS	NS	NS	NS	NS	NS
CS × D		***	***	*	***	***	NS
FM × CS × D		NS	NS	NS	NS	NS	NS

* Significant at $P \leq 0.05$; NS, not significant.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† CHEM, weed control by herbicide application; GRAZ, weed control by sheep grazing.

‡ CA, continuous alfalfa; CSW, continuous spring wheat; W-P/B-F, spring wheat-pea/barley hay-fallow.

§ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

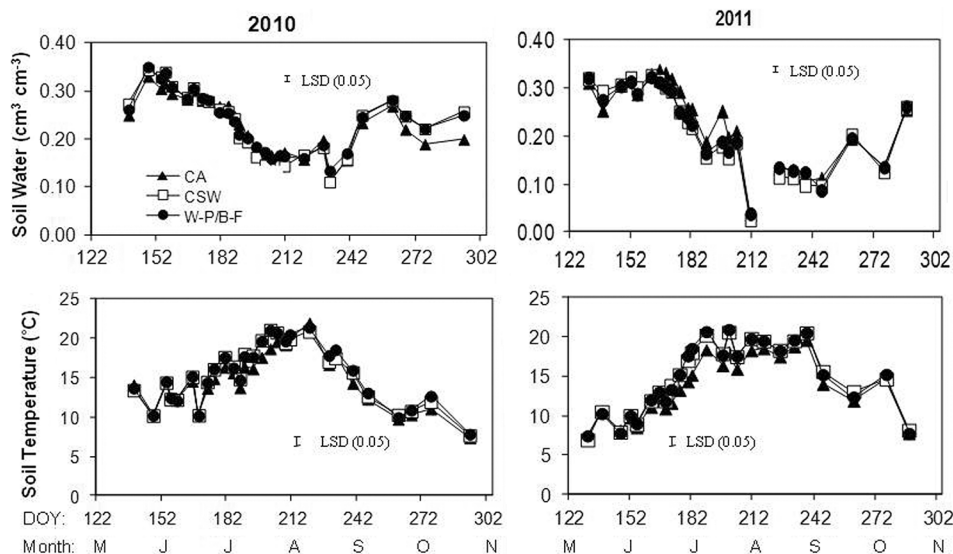


Fig. 2. Effect of cropping sequence on soil temperature and water content from May to October 2010 and 2011. Cropping sequences included continuous alfalfa (CA), continuous spring wheat (CSW), and a spring wheat-pea/barley hay-fallow rotation (W-P/B-F); DOY denotes day of the year and M to N denote months from May to November; LSD(0.05) is the least significant difference between treatments at $P = 0.05$.

(Table 1). In 2011, soil temperature was greater for CSW and W-P/B-F than CA under CHEM and GRAZ. Lower biomass yield ($4.1\text{--}5.1\text{ Mg ha}^{-1}$ in CSW and W-P/B-F vs. 7.1 Mg ha^{-1} in CA), followed by increased exposure of the soil during the fallow period, probably reduced shade intensity and increased soil temperature for CSW and W-P/B-F compared with CA. Sainju et al. (2008) reported that lower crop biomass yield reduces shade intensity and increases soil temperature. Averaged across treatments, soil temperature was 0.7°C (4.8%) higher in 2010 than in 2011.

Soil water content varied with measurement date and responded to precipitation events (Fig. 1 and 2). Water content was greater for CSW and W-P/B-F than CA in June, September, and October but greater for CA and W-P/B-F than CSW in July and August 2010 (Fig. 2). In 2011, water content was greater for CA

than CSW and W-P/B-F in June and July. Water content, averaged across measurement dates, was greater for W-P/B-F than CA and CSW under CHEM in 2010 and greater for CA than CSW and W-P/B-F under GRAZ in 2011 (Table 1). Averaged across fallow management and measurement dates, water content was greater for W-P/B-F than CA and CSW in 2010 but greater for CA than CSW and W-P/B-F in 2011. Similar to soil temperature, water content was $0.01\text{ m}^{-3}\text{ m}^{-3}$ (4.5%) higher in 2010 than in 2011.

The greater soil water content under CHEM with W-P/B-F in 2010 was probably a result of lower water use by pea/barley hay and increased water conservation during fallow. Pea/barley hay uses less soil water than durum because of early harvest, and the absence of plants during fallow increases soil water content (Lenssen et al., 2010). Although sheep grazing is effective in controlling weeds, it may not be as effective as herbicide application because some weeds and plants may survive for a longer period (Hatfield et al., 2007). As a result, surviving plants may use some soil water in the grazing treatment. This probably resulted in lower water content for all cropping sequences in the grazing treatment in 2010. In contrast, removal of alfalfa forage by sheep grazing probably reduced water uptake and increased soil water content under GRAZ with CA in 2011.

For the W-P/B-F rotation, soil temperature and water content were greater under fallow than under spring wheat and pea/barley hay in July and August 2010 and 2011 (Fig. 3). The absence of plants during fallow probably reduced shade intensity and water uptake, thereby increasing soil temperature and water content under fallow than under crops.

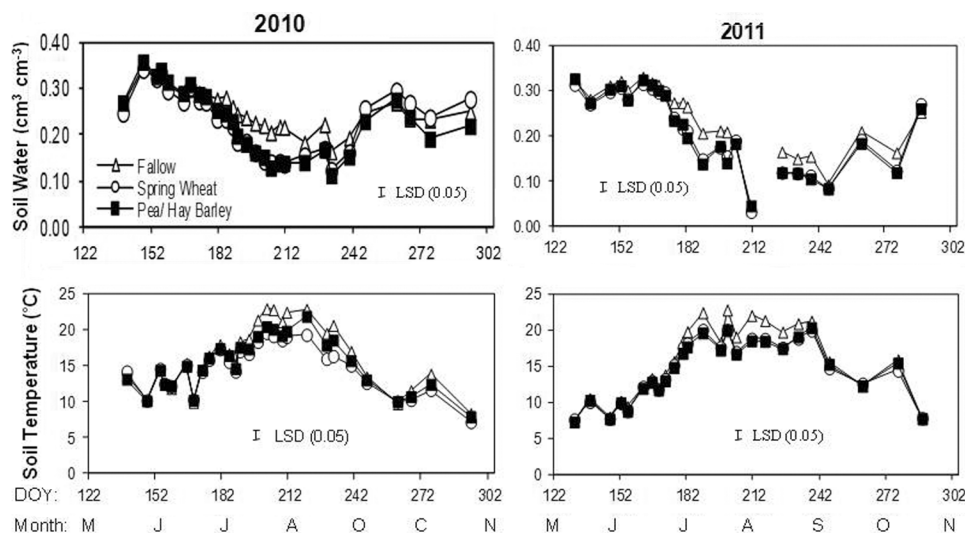


Fig. 3. Effect of crop species on soil temperature and water content from May to October 2010 and 2011 in the spring wheat-pea/barley hay-fallow rotation; DOY denotes day of the year and M to N denote months from May to November; LSD(0.05) is the least significant difference between treatments at $P = 0.05$.

Greenhouse Gas Emissions Carbon Dioxide

Carbon dioxide flux varied with cropping sequence and date of sampling in 2010 and 2011 (Table 2). Significant interactions were observed for fallow management \times cropping sequence, fallow management \times date of sampling, and cropping sequence \times date of sampling in 2010 and 2011. Fallow management did not influence CO_2 flux.

Carbon dioxide flux peaked following substantial precipitation (>12 mm) with increased soil temperature and water content from May to August in both years (Fig. 4–6). The flux ranged from 3 kg C ha⁻¹ d⁻¹ in June 2010 to 28 kg C ha⁻¹ d⁻¹ in July 2011 (Fig. 4 and 5). The peak value of CO₂ flux in this experiment was lower than the values of 80 to 160 kg C ha⁻¹ d⁻¹ under spring wheat in western Canada (Curtin et al., 2000) and 57 kg C ha⁻¹ d⁻¹ under malt barley in western North Dakota (Sainju et al., 2008), both measured by the dynamic chamber method, but greater than the value of 16 kg C ha⁻¹ d⁻¹ under fallow in North Dakota measured by the static chamber method (Liebig et al., 2010). Differences in soil and environmental conditions and management practices among locations and measurement methods can influence CO₂ fluxes (Sainju et al., 2012). Regardless of treatments and years, most of the CO₂ flux occurred from May to August (>80%). Because 30 to 50% of the total CO₂ flux is accounted for by root respiration (Curtin et al., 2000; Mosier et al., 2006), most of CO₂ flux during this period was probably due to root respiration as a result of active crop growth, with other fluxes from increased microbial activity and C mineralization due to higher soil temperature and water content (Fig. 2) (Curtin et al., 2000).

Carbon dioxide flux was greater under CHEM than GRAZ in mid-June and September but was greater under GRAZ than CHEM in May, late June, and early August in 2010 (Fig. 4). In 2011, CO₂ flux was greater under GRAZ than CHEM in late

May and July. Increased C substrate availability from sheep feces and urine returned to the soil during grazing probably increased microbial activity during increased soil temperature and water content, thereby increasing CO₂ fluxes under GRAZ compared with CHEM from May to August. Carbon dioxide flux was also greater for CA than CSW and W-P/B-F from June to September 2010 and in June and July 2011 (Fig. 5). Total CO₂ flux from May to October was greater under GRAZ with CA than the other treatments, except under CHEM with CA in 2010 and 2011 (Table 2). Averaged across fallow management, total CO₂ flux was greater for CA than CSW and W-P/B-F. Averaged across treatments, total CO₂ flux was greater ($P \geq 0.05$) in 2010 than in 2011.

The greater CO₂ flux for CA than CSW and W-P/B-F under CHEM and GRAZ treatments was probably due to increased root respiration as a result of higher belowground biomass in the perennial alfalfa than the annual crops. It has been reported that alfalfa has a larger root biomass than durum and annual forages (Sainju and Lenssen, 2011), and CO₂ flux is higher under a mixture of alfalfa and grasses than under annual crops (Sainju et al., 2008). Similarly, greater CO₂ flux for CSW than W-P/B-F under CHEM was probably a result of increased root respiration and/or belowground biomass residue returned to the soil because root respiration and the return of belowground biomass residue occurred every year in CSW compared with 2 out of 3 yr in W-P/B-F. Several researchers (Curtin et al., 2000; Sainju et al., 2008)

Table 2. Effects of fallow management and cropping sequence on total greenhouse gas fluxes from May to October 2010 and 2011.

Fallow management†	Cropping sequence‡	Total CO ₂ flux			Total N ₂ O flux			Total CH ₄ flux		
		2010	2011	Mean	2010	2011	Mean	2010	2011	Mean
		Mg C ha ⁻¹			kg N ha ⁻¹			kg C ha ⁻¹		
CHEM	CA	2.33 ab§	1.67 ab	2.00 ab	0.84 d	0.42 c	0.63 d	0.21a	0.10 a	0.16 a
	CSW	2.03 b	1.51 b	1.77 b	4.11 a	0.79 b	2.35 a	0.13a	0.04 a	0.08 a
	W-P/B-F	1.64 c	1.22 c	1.43 c	1.62 c	0.51 c	1.03 c	0.15a	0.03 a	0.09 a
GRAZ	CA	2.47 a	1.86 a	2.17 a	3.14 b	0.39 c	1.76 b	0.24a	0.01 a	0.17 a
	CSW	1.77 bc	1.24 c	1.51 bc	3.92 a	1.35 a	2.58 a	0.22a	−0.04 a	0.09 a
	W-P/B-F	1.87 bc	1.40 bc	1.63 bc	1.92 c	0.74 b	1.33 bc	0.14a	−0.10 a	0.07 a
<u>Means</u>										
CHEM		2.00 a	1.47 a	1.73 a	2.19 a	0.57 a	1.33 a	0.16a	0.02 a	0.11 a
GRAZ		2.04 a	1.50 a	1.77 a	2.99 a	0.83 a	1.89 a	0.20a	0.02 a	0.11 a
	CA	2.40 a	1.77 a	2.08 a	1.99 b	0.40 c	1.20 b	0.22a	0.03 a	0.16 a
	CSW	1.90 b	1.37 b	1.64 b	4.02 a	1.07 a	2.46 a	0.18ab	0.02 b	0.09 b
	W-P/B-F	1.75 b	1.31 b	1.53 c	1.77 b	0.62 b	1.18 b	0.15b	0.02 b	0.08 b
<u>Significance</u>										
Fallow management (FM)		NS	NS	NS	NS	NS	NS	NS	NS	NS
Cropping sequence (CS)		***	***	***	***	***	***	*	*	*
FM × CS		***	***	***	***	***	**	NS	NS	NS
Date of sampling (D)		***	***	***	***	***	***	***	***	***
FM × D		**	*	NS	*	NS	NS	***	***	NS
CS × D		**	***	NS	***	***	***	NS	*	NS
FM × CS × D		NS	NS	NS	NS	NS	***	NS	NS	NS

* Significant at $P \leq 0.05$; NS, not significant.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† CHEM, weed control by herbicide application; GRAZ, weed control by sheep grazing.

‡ CA, continuous alfalfa; CSW, continuous spring wheat; W-P/B-F, spring wheat-pea/barley hay-fallow.

§ Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

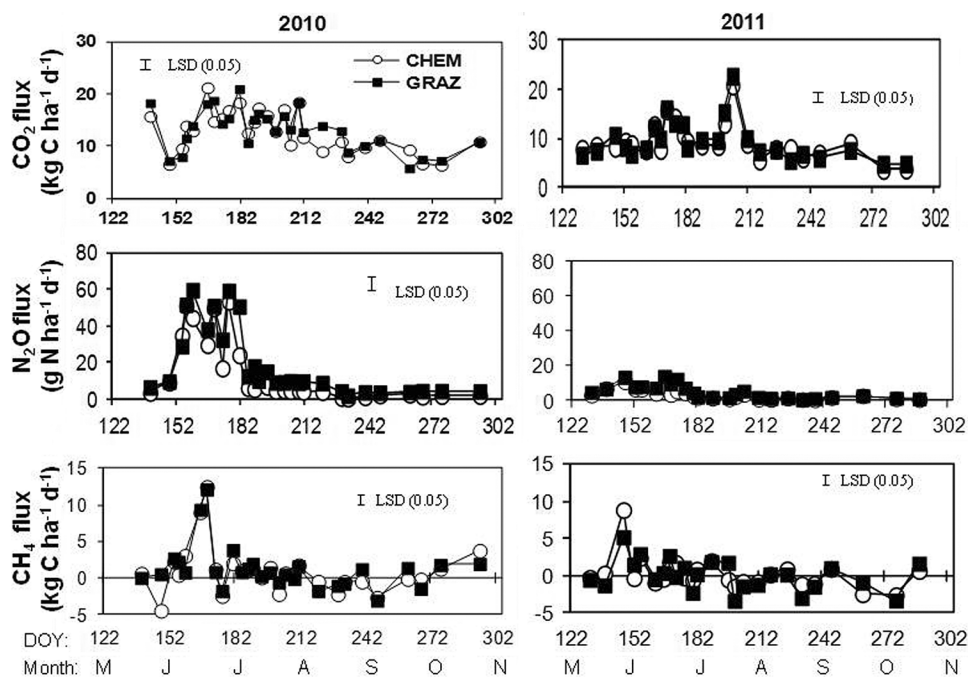


Fig. 4. Effect of fallow management on surface soil CO_2 , N_2O , and CH_4 fluxes from May to October 2010 and 2011. Fallow management consisted of either herbicide application for weed control (CHEM) or grazing by sheep (GRAZ); DOY denotes day of the year and M to N denote months from May to November; LSD(0.05) is the least significant difference between treatments at $P = 0.05$.

have also reported greater CO_2 fluxes in cropping systems with an increased amount of crop residue returned to the soil. The return of feces and urine during sheep grazing may have compromised CO_2 fluxes, thereby resulting in similar CO_2 fluxes between CSW and W-P/B-F under GRAZ. Greater CO_2 flux in 2010

respiration, greater CO_2 flux under pea/barley hay than spring wheat and fallow in 2010 was probably a result of higher root respiration and/or C substrate availability. In 2010, total biomass yield was greater in pea/barley hay (6.8 Mg ha^{-1}) than spring wheat (5.1 mg ha^{-1}). Similarly, soil total C content at 0

than in 2011 was probably a result of higher precipitation and soil temperature and water content during the measurement period (Tables 1 and 2; Fig. 1).

To evaluate the effect of crop species on CO_2 fluxes, data were analyzed by cropping phase within W-P/B-F (Fig. 6). Carbon dioxide flux was greater under pea/barley hay than spring wheat and fallow from May to July 2010 but was greater under spring wheat than fallow in May 2011 and greater under spring wheat and fallow than pea/barley hay in August 2011 (Fig. 6). Total CO_2 flux from May to October was greater under pea/barley hay than spring wheat and fallow in 2010 but not different among crop species in 2011 (Table 3). Assuming that increased aboveground biomass also increased the below-ground biomass and therefore root

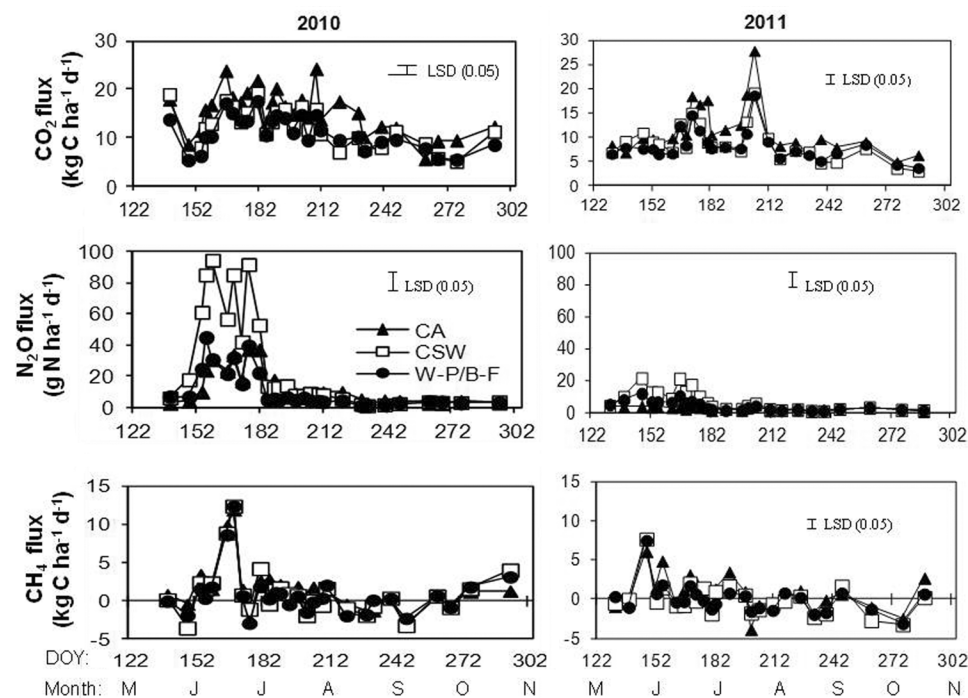


Fig. 5. Effect of cropping sequence on surface soil CO_2 , N_2O , and CH_4 fluxes from May to October, 2010 and 2011. Cropping sequences included continuous alfalfa (CA), continuous spring wheat (CSW), and a spring wheat–pea/barley hay–fallow rotation (W-P/B-F); DOY denotes day of the year and M to N denote months from May to November; LSD(0.05) is the least significant difference between treatments at $P = 0.05$.

to 15 cm was greater under pea/barley hay (53.1 Mg ha^{-1}) than spring wheat (50.0 Mg ha^{-1}) and fallow (48.7 Mg ha^{-1}). Although soil temperature and water content were greater under fallow (Fig. 3; Table 3), they had minimal effects on CO_2 flux. This shows that substrate availability and root respiration are probably more important than soil temperature and water content for CO_2 emissions under dryland cropping systems.

Nitrous Oxide

Similar to CO_2 flux, N_2O flux varied with cropping sequence and date of sampling but not with fallow management in 2010 and 2011 (Table 2). Interactions were significant for cropping sequence \times fallow management and cropping sequence \times date of sampling in 2010 and 2011 and fallow management \times date of sampling in 2010.

Nitrous oxide flux peaked from 1 g N ha⁻¹ d⁻¹ in May 2011 to 90 g N ha⁻¹ d⁻¹ in June 2010 (Fig. 4–6). Most of the fluxes (>70%) occurred from May to July, regardless of treatments and years. The N₂O flux range observed in this experiment was within or greater than the range of –8 to 21 g N ha⁻¹ d⁻¹ under a spring wheat–pea rotation and fallow in western Montana and central North Dakota (Dusenbury et al., 2008; Liebig et al., 2010). The greater N₂O flux from May to July was probably due to both N fertilization and increased soil water content due to substantial precipitation (>12 mm) (Fig. 1–3). Several researchers (Mosier et al., 2006; Dusenbury et al., 2008; Liebig et al., 2010) have reported increased N₂O fluxes immediately after N fertilization and substantial precipitation.

Nitrous oxide flux was greater under GRAZ than CHEM in June and July 2010 (Fig. 4). Similarly, N₂O flux was greater for CSW than CA and W-P/B-F in June 2010 and greater for CSW and W-P/B-F than CA in June and July 2011 (Fig. 5). Total N₂O flux from May to October was greater for CSW than CA and W-P/B-F under CHEM and GRAZ in 2010 and 2011 (Table 2). Averaged across fallow management systems, total N₂O flux was greater for CSW than CA and W-P/B-F in 2010 and greater for CSW and W-P/B-F than CA in 2011. Averaged across treatments, N₂O flux was greater ($P \leq 0.05$) in 2010 than 2011.

The greater N₂O flux under GRAZ than CHEM in June and July 2010 was probably due to sheep feces and urine returned to the soil from grazing during periods of higher soil temperature and water content. Similarly, greater N₂O flux for CSW and W-P/B-F than CA in June and July 2010 and 2011 was clearly a result of N fertilization to spring wheat and pea/barley hay but not to alfalfa. Increased N substrate availability due to N fertilization has been known to increase N₂O flux due to enhanced nitrification (Mosier et al., 2006; Dusenbury et al., 2008). Although legumes can produce significant N₂O emissions due to their lower C/N ratio than nonlegumes (Mosier et al., 2006; Dusenbury et al., 2008), N₂O flux from alfalfa in CA had been minimal. Greater N₂O flux in 2010 than in 2011 may be a result

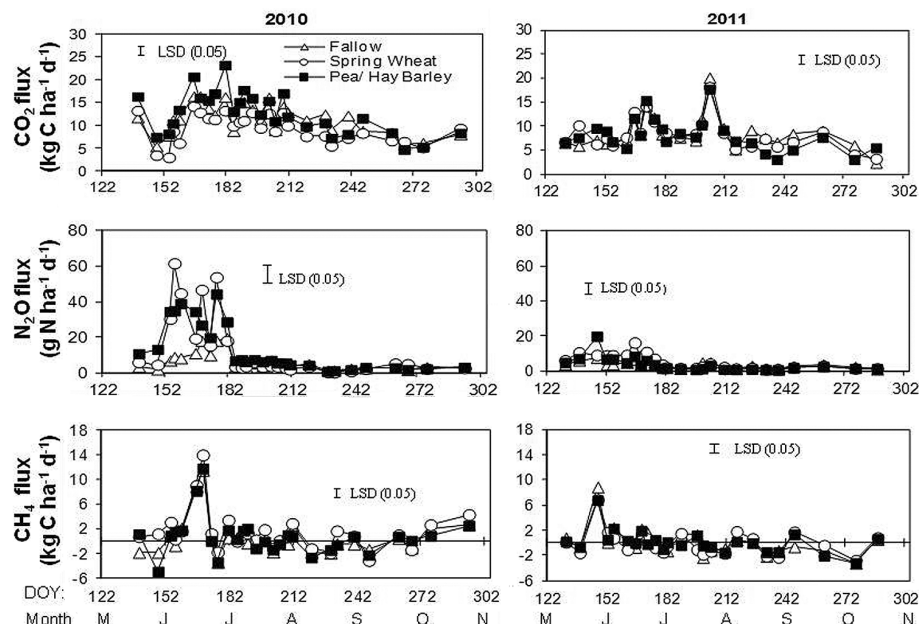


Fig. 6. Effect of crop species on surface soil CO₂, N₂O, and CH₄ fluxes from May to October 2010 and 2011 in the spring wheat–pea/barley hay–fallow rotation; DOY denotes day of the year and M to N denote months from May to November; LSD(0.05) is the least significant difference between treatments at $P = 0.05$.

of increased precipitation with increased soil temperature and water content (Fig. 1 and 2; Table 1) that probably enhanced microbial activity and N mineralization (Parkin and Kaspar, 2003; Dusenbury et al., 2008; Liebig et al., 2010).

Among crop species within W-P/B-F, N₂O flux was greater under spring wheat and pea/barley hay than fallow in June and July 2010 and 2011 (Fig. 6). Total N₂O flux from May to October was greater under spring wheat and pea/barley hay than fallow in 2010 and greater under spring wheat than pea/barley hay and fallow in 2011 (Table 3). Although soil temperature and water content were greater under fallow than spring wheat and pea/barley hay, N fertilization at planting in May probably increased N₂O flux under spring wheat and pea/barley hay. Most of the nitrification process due to N fertilization probably occurred in June and July, thereby resulting in greater N₂O flux under spring wheat and pea/barley hay during this period. This shows that N fertilization was probably the dominant factor for N₂O emissions rather than soil temperature and water content.

Methane

Methane flux varied with cropping sequence and date of sampling in 2010 and 2011, with significant fallow management ×

Table 3. Effect of crop species on average soil temperature and water content and total greenhouse gas fluxes in a spring wheat–pea/barley hay–fallow rotation from May to October 2010 and 2011.

Crop species	Soil water content		Soil temperature		Total CO ₂ flux		Total N ₂ O flux		Total CH ₄ flux	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
	m ³ m ⁻³		°C		Mg C ha ⁻¹		kg N ha ⁻¹		kg C ha ⁻¹	
Fallow	0.255 a†	0.236 a	16.18 a	15.57 a	1.81 b	1.34 a	0.98 b	0.52 b	0.09 b	0.01 a
Spring wheat	0.229 b	0.212 b	14.74 c	14.51 b	1.47 c	1.31 a	2.03 a	0.79 a	0.24 a	–0.01 a
Pea/barley	0.227 b	0.211 b	15.27 b	14.41 b	1.98 a	1.27 a	2.08 a	0.57 b	0.11 b	0.02 a

† Numbers followed by a different letter within a column are significantly different at $P \leq 0.05$ by the least square means test.

date of sampling interaction in both years and cropping sequence \times date of sampling interaction in 2011 (Table 2). The CH_4 flux ranged from $-5 \text{ g C ha}^{-1} \text{ d}^{-1}$ in May 2010 to $15 \text{ g C ha}^{-1} \text{ d}^{-1}$ in June 2010 (Fig. 4–6). This range was within or greater than the range of -12 to $5 \text{ g C ha}^{-1} \text{ d}^{-1}$ under dryland spring wheat–fallow and fallow systems in western Nebraska and central North Dakota (Kessavalou et al., 1998; Liebig et al., 2010). About half of the flux was negative, suggesting CH_4 uptake by the soil. It is not unusual for dryland soil to act as a sink for CH_4 due to its consumption by methanotrophs (Sylvia et al., 1998). Methane uptake can be greater as soils dry (Liebig et al., 2010).

Methane flux was greater under GRAZ than CHEM in late May 2010 and mid-July 2011 but was greater under CHEM than GRAZ in early June 2010 and 2011 (Fig. 4). Similarly, CH_4 flux was greater for CA than CSW and W-P/B-F in June, early July, and October 2011 (Fig. 5). Averaged across fallow management practices, total CH_4 flux from May to October was greater for CA than W-P/B-F in 2010 and greater for CA than CSW and W-P/B-F in 2011 (Table 2). Averaged across treatments, total CH_4 flux was greater ($P \geq 0.05$) in 2010 than in 2011.

Although CH_4 flux varied with fallow management at various sampling dates (Fig. 4) and animal manure has been reported to be a significant source of CH_4 flux (USEPA, 2011), sheep grazing did not appear to produce substantial CH_4 emissions compared with herbicide application for weed control because the total CH_4 flux from May to October was not influenced by fallow management (Table 2). The reasons for greater CH_4 flux for CA than CSW and W-P/B-F were not known. One possible reason could be greater C substrate availability due to higher root biomass and SOC in alfalfa than annual crops (Sainju and Lenssen, 2011) that increased CH_4 flux, similar to CO_2 flux. Greater CH_4 flux in 2010 than in 2011 was probably a result of higher precipitation, with increased soil temperature and water content (Tables 1 and 2) that enhanced anaerobic C mineralization.

Within W-P/B-F, CH_4 flux was greater under spring wheat than pea/barley hay and fallow from June to October 2010 and in mid-July and mid-August 2011 (Fig. 6). Total CH_4 flux from May to October was greater under spring wheat than fallow and pea/hay barley in 2010 (Table 3). Because N fertilizer was applied to spring wheat and pea/barley hay but not to fallow, it appears that an increased N fertilization rate promoted CH_4 flux under spring wheat, especially during periods with higher precipitation. Several researchers (Bronson and Mosier, 1994; Powlson et al., 1997) have reported that N fertilization increased soil CH_4 flux compared with no N fertilization.

Global Warming Potential and Greenhouse Gas Intensity

The CO_2 equivalent of N fertilization to crops, annualized aboveground grain and/or biomass yields, and the previous year's crop root and rhizodeposit C varied with cropping sequences and years (Table 4). Similarly, net GWP and GHGI based on soil respiration and SOC varied with fallow management, cropping sequences, and years. Significant interactions occurred for fallow

management \times cropping sequence and fallow management \times cropping sequence \times year for all parameters.

Estimated CO_2 emissions from farm operations varied with treatments, with higher emissions under CHEM than GRAZ (Tables 4 and 5). Equipments used for tillage, planting, herbicide application, and harvest in annual crops resulted in increased CO_2 emissions for CSW and W-P/B-F compared with those used for initial planting and harvest for alfalfa in CA. Sheep grazing eliminated the need for aboveground biomass harvest and therefore reduced CO_2 emissions under GRAZ compared with CHEM. Differences in CO_2 emissions due to N fertilization among treatments and years was due to variations in N fertilization rates to crops, which depended on yield goals and the previous year's residual soil $\text{NO}_3\text{-N}$ level to a depth of 60 cm after crop harvest because the N rate in each treatment and year was adjusted to the soil $\text{NO}_3\text{-N}$ content. While no N fertilizer was applied to CA, the N rate was higher for CSW, thereby resulting in greater CO_2 emissions due to N fertilization, than W-P/B-F. Continuous cropping and a greater N fertilizer requirement for spring wheat than for pea/barley hay resulted in a greater N rate and therefore higher CO_2 emissions for CSW than W-P/B-F.

As reported by several researchers (Robertson et al., 2000; Mosier et al., 2006), N_2O flux contributed largely to the net GWP based on SOC, and CO_2 flux contributed largely to the net GWP based on soil respiration, while the contribution from CH_4 flux to the net GWP was minimal (Tables 4 and 5). In contrast, the estimated CH_4 flux from enteric fermentation contributed a significant portion of the net GWP under the GRAZ treatment. The flux varied with the number and duration of sheep grazed in each treatment and year, which ranged from $539 \text{ sheep ha}^{-1} \text{ yr}^{-1}$ for CA in 2010 and 2011 to $4280 \text{ sheep ha}^{-1} \text{ yr}^{-1}$ for W-P/B-F in 2010 under the GRAZ treatment. The longer duration of sheep grazing to control weeds during fallow periods (including summer fallow) increased the CO_2 equivalent of CH_4 flux due to enteric fermentation in W-P/B-F.

The estimated previous year's crop root and rhizodeposit C was greater for CA but lower for W-P/B-F than CSW under both CHEM and GRAZ (Table 5). It was not surprising to observe greater root and rhizodeposit C in perennial crops, such as alfalfa, due to higher belowground biomass yield than annual crops (Sainju and Lenssen, 2011). In contrast, lower root and rhizodeposit C for W-P/B-F than CSW was probably due to the absence of crops during fallow. Annualized aboveground crop grain and/or biomass yield, however, was greater for CSW than the other cropping sequences under CHEM and GRAZ in 2010. In 2011, annualized crop yield was greater under GRAZ with CA than the other treatments, except under CHEM with CA. Continuous cropping probably increased annualized grain and/or biomass yield for CSW and CA compared with W-P/B-F. Crop yields were also greater in 2010 than in 2011 due to higher precipitation during the growing season (Fig. 1).

The removal of aboveground grain and/or biomass in spring wheat, pea/barley hay, and alfalfa due to harvest and sheep grazing probably resulted in negative soil C sequestration rates in all

Table 4. Fallow management and cropping sequence effect on net global warming potential (GWP) and greenhouse gas intensity (GHGI) based on soil respiration and soil organic C (SOC) averaged across years.

Fallow management†	Cropping sequence‡	Farm operation (A)\$	N fertilizer (B)¶	N ₂ O flux (C)#	CH ₄ flux enteric fermentation (D)#	CH ₄ flux enteric fermentation (E)††	Soil respiration (F)‡‡	Previous year's crop root C (G)§§	C sequestration rate (H)¶¶	Net GWP (respiration) (I)##	Net GWP (SOC) (J)+++	Annual grain or biomass (K)	GHGI (respiration) (L)###	GHGI (SOC) (M)###
CHEM	CA	28	0 d	774 d	8 a	0	7300 ab	3139 a	-117 a	4970 c	927 d	6407 b	0.78d	0.15c
	CSW	85	432 a	3182 a	5 a	0	6486 b	1449 b	-1797 c	8740 a	5500 b	7245 a	1.18bc	0.73b
	W-P/B-F	85	229 c	1270 c	5 a	0	5239 c	933 b	-2049 c	5894 bc	3638 c	5632 c	1.04cd	0.65b
GRAZ	CA	14	0 d	2227 b	8 a	527	7873 a	3620 a	-670 b	7030 b	3447 c	7387 a	0.95d	0.47c
	CSW	65	366 b	3175 a	5 a	693	5480 bc	1273 b	-280 a	8574 a	4647 b	6366 b	1.44b	0.73b
	W-P/B-F	65	296 c	1641 bc	3 a	1692	5978 bc	807 b	-3335 d	8868 a	7031 a	4750 d	1.86a	1.48a
Significance														
Fallow management (FM)	—	NS	NS	NS	NS	—	NS	NS	NS	*	*	NS	*	*
Cropping sequence (CS)	—	***	***	**	NS	—	***	***	**	**	***	***	***	***
FM × CS	—	**	**	NS	NS	—	*	*	*	*	***	*	*	***
Year (Y)	—	***	***	***	*	—	***	***	—	***	**	***	***	***
FM × Y	—	*	*	NS	NS	—	NS	NS	—	NS	NS	NS	NS	NS
CS × Y	—	***	***	*	NS	—	NS	***	—	*	*	***	**	NS
FM × CS × Y	—	***	***	*	NS	—	*	***	—	*	*	***	*	*

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† CHEM, herbicide applied to control weeds; GRAZ, sheep grazed to control weeds.

‡ CA, continuous alfalfa; CSW, continuous spring wheat; W-P/B-F, spring wheat-pea/barley hay-fallow.

§ Fuel combustion for equipment used for planting, fertilization, herbicide and pesticide applications, and harvest (estimated from West and Marland, 2002).

¶ N fertilizer production = 45.5 kg CO₂ ha⁻¹ for application + 3.0 kg CO₂ kg⁻¹ N applied (Follett, 2001).

Total gas flux from May to October + 12% for CO₂, 15% for N₂O, and 30% for CH₄ of the total flux from November to April (Liebig et al., 2010); 1 kg N₂O ha⁻¹ = 298 kg CO₂ ha⁻¹, 1 kg CH₄ ha⁻¹ = 25 kg CO₂ ha⁻¹ (Intergovernmental Panel on Climate Change, 2007).

†† Enteric fermentation of sheep for CH₄ flux = 488 g CO₂ flux sheep⁻¹ d⁻¹ (Judd et al., 1999).

‡‡ Soil respiration = 0.7 × CO₂ flux (Mosier et al., 2006).

§§ Estimated previous year's root C (Sainju and Lenssen, 2011)

¶¶ Calculated from linear regression of change in soil organic C at the 0–15-cm depth from 2009 to 2011.

A + B + C + D + E + F – G.

††† A + B + C + D + E – H.

L (kg CO₂ equivalent kg⁻¹ grain or biomass) = I/K; M (kg CO₂ equivalent kg⁻¹ grain or biomass) = J/K.

\$\$\$ Not significant.

Table 5. Fallow management and cropping sequence effect on net global warming potential (GWP) and greenhouse gas intensity (GHGI) based on soil respiration and soil organic C (SOC) in 2010 and 2011.

		kg CO ₂ equivalent ha ⁻¹										kg ha ⁻¹	— kg CO ₂ eq. kg ⁻¹ yield—		
		2010													
CHEM	CA	28	0 d	1038 d	11 a	0	0	8371 ab	3139 a	-117 a	6309 b	1194 d	6407 bc	0.98 c	0.19 c
	CSW	85	480 b	5396 a	7 a	0	0	7281 b	1770 b	-1797 c	11479 a	7765 a	8849 a	1.30 b	0.88 b
	W-P/B-F	85	303 c	1921 c	8 a	0	0	5840 c	957 c	-2049 c	7200 b	4366 bc	5632 c	1.28 b	0.77 b
	CA	14	0 d	3977 b	12 a	527	8797 a	3619 a	-670 b	9706 a	5201 b	7387 b	1.32 b	0.70 b	
GRAZ	CSW	65	512 a	4706 a	12 a	1123	6265 c	1798 b	-280 a	10885 a	6698 ab	8989 a	1.21 b	0.75 b	
	W-P/B-F	65	323 c	2379 c	8 a	2088	6708 bc	829 c	-3335 d	10742 a	8197 a	4879 c	2.20 a	1.68 a	
		2011													
CHEM	CA	28	0 d	509 c	5 a	0	0	6228 ab	3139 a	-117 a	3631 b	659 d	6407 ab	0.56 c	0.10 d
	CSW	85	383 a	967 b	2 a	0	0	5691 b	1128 b	-1797 c	6000 a	3234 b	5640 b	1.06 b	0.58 bc
	W-P/B-F	85	155 c	619 c	1 a	0	0	4638 c	911 b	-2049 c	4588 b	2909 b	5361 bc	0.81 b	0.52 c
	CA	14	0 d	477 c	4 a	527	6948 a	3620 a	-670 b	4351 b	1692 c	7387 a	0.59 c	0.23 d	
GRAZ	CSW	65	348 a	1644 a	3 a	263	4694 bc	748 b	-280 a	6263 a	2597 b	3742 d	1.67 a	0.70 b	
	W-P/B-F	65	269 b	903 b	-1 a	1295	5248 bc	785 b	-3335 d	6994 a	5865 a	4620 cd	1.51 a	1.27 a	

† CHEM, herbicide applied to control weeds; GRAZ, sheep grazed to control weeds.

‡ CA, continuous alfalfa; CSW, continuous spring wheat; W-P/B-F, spring wheat-pea/barley hay-fallow.

§ Fuel combustion for equipment used for planting, fertilization, herbicide and pesticide applications, and harvest (estimated from West and Marland, 2002).

¶ N fertilizer production = 45.5 kg CO₂ ha⁻¹ for application + 3.0 kg CO₂ kg⁻¹ N applied (Follett, 2001).

Total gas flux from May to October + 12% for CO₂, 15% for N₂O, and 30% for CH₄ of the total flux from November to April (Liebig et al., 2010); 1 kg N₂O ha⁻¹ = 298 kg CO₂ ha⁻¹, 1 kg CH₄ ha⁻¹ = 25 kg CO₂ ha⁻¹ (Intergovernmental Panel on Climate Change, 2007).

†† Enteric fermentation of sheep for CH₄ flux = 488 g CO₂ flux sheep⁻¹ d⁻¹ (Judd et al., 1999).

Soil respiration = 0.7 × CO₂ flux (Mosier et al., 2006).

§§ Estimated previous year's root C (Sainju and Lenssen, 2011)

¶¶ Calculated from linear regression of change in soil organic C at the 0–15-cm depth from 2009 to 2011.

A + B + C + D + E + F – G.

††† A + B + C + D + E – H.

L (kg CO₂ equivalent kg⁻¹ grain or biomass) = I/K; M (kg CO₂ equivalent kg⁻¹ grain or biomass) = J/K.

treatments (Tables 4 and 5). It has been known that crop residue removal can reduce soil C storage and C sequestration rates compared with not removing residue (Stetson et al., 2012). Greater C was lost from W-P/B-F than the other cropping sequences, probably due to a smaller amount of belowground crop residues returned to the soil as a result of the absence of crops during fallow. Fallowing in a crop–fallow rotation can reduce soil C storage compared with a continuous cropping system (Aase and Pikkul, 1995; Sainju and Lenssen, 2011).

Net GWP based on soil respiration was greater for CSW than CA and W-P/B-F under CHEM in both years but was either not different among cropping sequences in 2010 or greater for CSW and W-P/B-F than CA under GRAZ in 2011 (Table 5). Averaged across years, net GWP was greater under CHEM with CSW and greater under GRAZ with CSW and W-P/B-F than other treatments (Table 4). Although CO₂ flux due to soil respiration was higher for CA, greater N₂O flux due to an increased N fertilization rate to CSW, followed by a lower previous year's crop root and rhizodeposit C probably increased net GWP based on soil respiration under CHEM and GRAZ with CSW. Mosier et al. (2006) also found that a greater N₂O flux due to an increased N fertilization rate, followed by a smaller amount of crop residue returned to the soil, increased net GWP based on soil respiration in no-till compared with conventionally tilled soils. Similarly, greater CH₄ flux due to increased enteric fermentation, followed by a lower previous year's root and rhizodeposit C probably increased net GWP based on soil respiration under GRAZ with W-P/B-F. Our results showed that herbicide application to control weeds in perennial crops (alfalfa) rather than sheep grazing in annual crop residues can reduce net GWP based on soil respiration.

Net GWP based on SOC was greater for CSW than CA and W-P/B-F under CHEM but greater for W-P/B-F than CA under GRAZ in 2010 (Table 5). In 2011, net GWP was greater under GRAZ with W-P/B-F than the other treatments. Averaged across years, net GWP was greater under GRAZ with W-P/B-F than the other treatments (Table 4). Increased CH₄ flux due to greater enteric fermentation, followed by a lower C sequestration rate as a result of reduced C inputs and enhanced SOC mineralization due to fallow, probably increased GWP under GRAZ with W-P/B-F. Schonbach et al. (2012) also reported that the net GHG balance increased with increased intensity of sheep grazing due to enhanced CH₄ flux from enteric fermentation in a temperate steppe ecosystem. Similar to GWP based on soil respiration, herbicide application to control weeds in alfalfa rather than sheep grazing in annual crop residues can reduce GWP based on SOC.

Compared with the other treatments, GHGI based on soil respiration was greater under GRAZ with W-P/B-F in 2010 and greater under GRAZ with CSW and W-P/B-F in 2011 (Table 5). Similarly, GHGI based on SOC was greater under GRAZ with W-P/B-F than the other treatments in 2010 and 2011. Averaged across years, both GHGI based on soil respiration and SOC were greater under GRAZ with W-P/B-F than the other

treatments (Table 4). Greater net GWP, followed by lower annualized grain and/or biomass yield, probably increased GHGI under GRAZ with W-P/B-F. Because of lower GHGI based on soil respiration and SOC, herbicide application to control weeds in perennial crops instead of sheep grazing in annual crop residues may be used to reduce net GHG emissions per unit crop yield, a case similar to that observed for net GWP.

Higher net GWP and GHGI based on soil respiration and SOC under GRAZ with W-P/B-F than the other treatments suggests that sheep grazing in dryland cropping systems containing fallow in the rotation may not reduce net GHG emissions compared with the conventional continuous annual cropping system where herbicide is used to control weeds (CHEM with CSW). Because sheep were kept inside the barn before bringing them to graze in plots, we assumed that CH₄ emitted from them as a result of enteric fermentation from the food eaten in the barn a day before grazing would be negligible. It was not known if letting the sheep graze for a longer period during fallow constituted excessive grazing, even though enough crop residues were left on the ground to control soil erosion. Moderate sheep grazing can increase SOC storage, but excessive grazing can lower its level (Judd et al., 1999; Schonbach et al., 2012). If the duration of grazing in fallow plots or the length of the fallow period can be reduced, sheep grazing may reduce GHG emissions by increasing C sequestration.

CONCLUSIONS

Sheep grazing and herbicide application for weed control in annual (CSW and W-P/B-F) and perennial (CA) cropping systems had variable effects on GHG emissions, net GWP, and GHGI in 2010 and 2011. In contrast to our hypothesis, sheep grazing in a perennial cropping system did not reduce GHG emissions and net GWP and GHGI based on soil respiration and SOC compared with herbicide application for weed control in annual cropping systems. In contrast, herbicide application for weed control in the perennial cropping system reduced net GWP and GHGI compared with sheep grazing in annual cropping systems. The perennial cropping system produced greater CO₂ and CH₄ emissions, probably due to greater root respiration, than annual cropping systems. A greater N fertilization rate, however, increased N₂O emissions in annual compared with perennial cropping systems. Increased CH₄ emissions due to enteric fermentation by sheep during a longer period of grazing, followed by a smaller amount of crop residue returned to the soil during fallow and a lower C sequestration rate, probably increased net GWP and GHGI based on soil respiration and SOC in the W-P/B-F rotation grazed by sheep than the other treatments. Sheep grazing in a dryland crop–fallow rotation may be less effective to mitigate GHG emissions and GWP than herbicide application for weed control in a conventional continuous cropping system. Reducing the duration of grazing in fallow plots, however, may reduce GHG emissions. Although long-term studies may be needed to account for high variability of GHG emissions and crop yields from year to year due variations in climatic condition,

resource constraints may be a limiting factor for such studies because GHG measurement is a labor-intensive process.

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